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Title: Deconvolution of a laser-induced neutron time-of-flight spectrum

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Deconvolution of a laser-induced neutron time-of-flight spectrum

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LA-UR-18-xxxxx

Outline

- Experiment history and description (brief)
- A look at the raw data
- Analysis strategy
  - neutron light output
  - MCNP response functions
  - matrix inversion
- Validation of the analysis method
- experimental results
- summary and unresolved issues

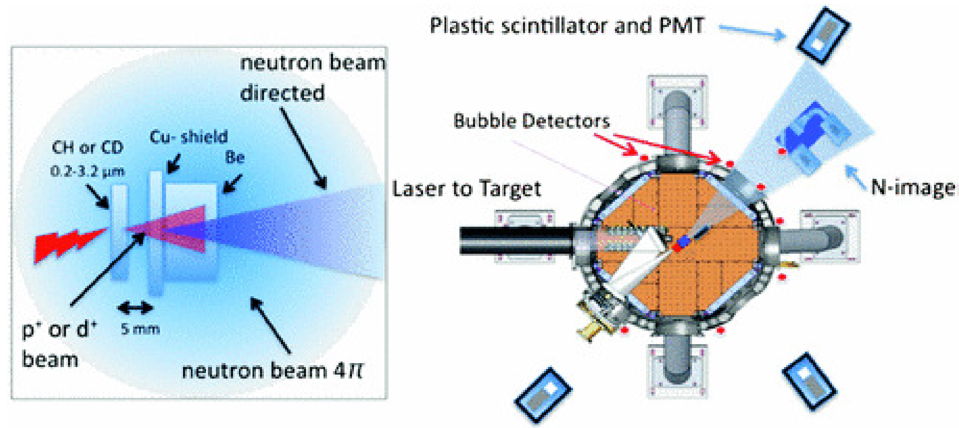
Neutron production tests with TRIDENT began in 2012

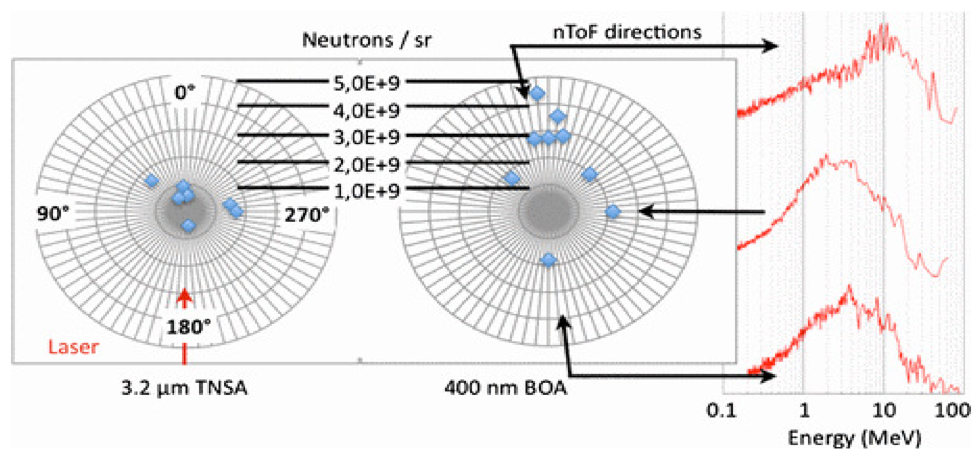
Markus Roth (Darmstadt) et al.,

Phys. Rev. Lett. 110, 044802 (2013)

- $\approx 5 \times 10^9$ n/sr/pulse
- Several detector types:
  - bubble
  - ^{3}He
  - plastic scintillator
- spectra presented incorrectly:

  TOF $\rightarrow E_n$





history.plt: 10 Jul 2018 18:53:35

Analysis of the plastic scintillator data was (is) quite challenging

- The plastic scintillators were 101.6-mm x 18.2 mm (4-in diam) at ~3 m inside the target room
- very complicated neutron environment:
  - close proximity to massive scatterers
  - very thick x-ray attenuators (10-in Pb) directly in front
- The plastic scintillator detectors were operated in current mode:
  - ~10^6 neutron interactions/pulse
  - no way to detect and count individual neutrons
  - time-of-flight (TOF) spectrum consists of a digitized oscilloscope trace of the photomultiplier output

The present set of TRIDENT data was obtained in 2015

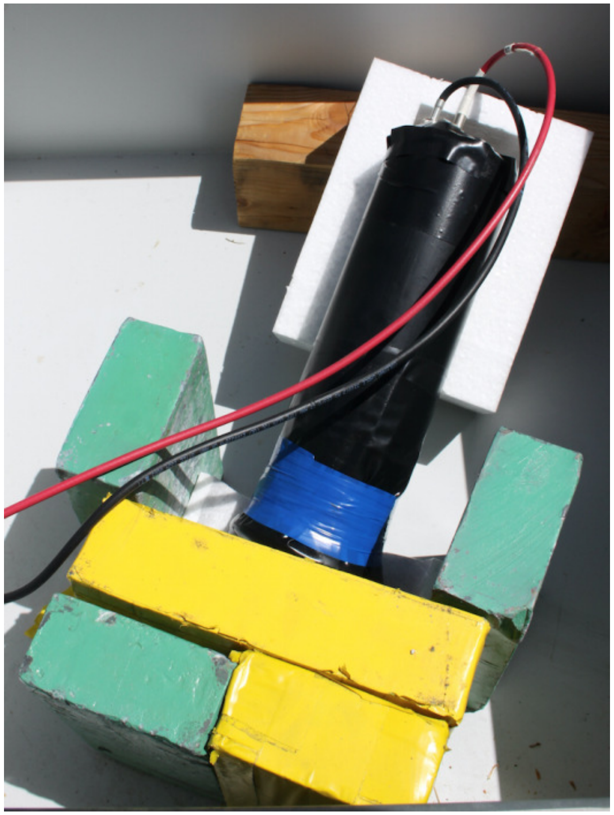
Some improvements were implemented to obtain better neutron TOF measurements:

- detector moved outside the building (6.2 m): cleaner environment
- thinner x-ray attenuator (4-in Pb versus 10 in) (less scatter)
- reconfigured plastic-scintillator detector:
  - PMT with 6 dynodes (XP4362B)
    (cut down dynode multiplication)
  - smaller scintillator diameter (3-in versus 4-in) x 18.2 mm thick
    (reduce charge depletion in photocathode)
  - specially designed tapered voltage divider
    (fast charge collection without space-charge effects)

The 2015 measurements were made in a cleaner radiation environment

detector outside building at 6.2 m

4-in Pb attenuator

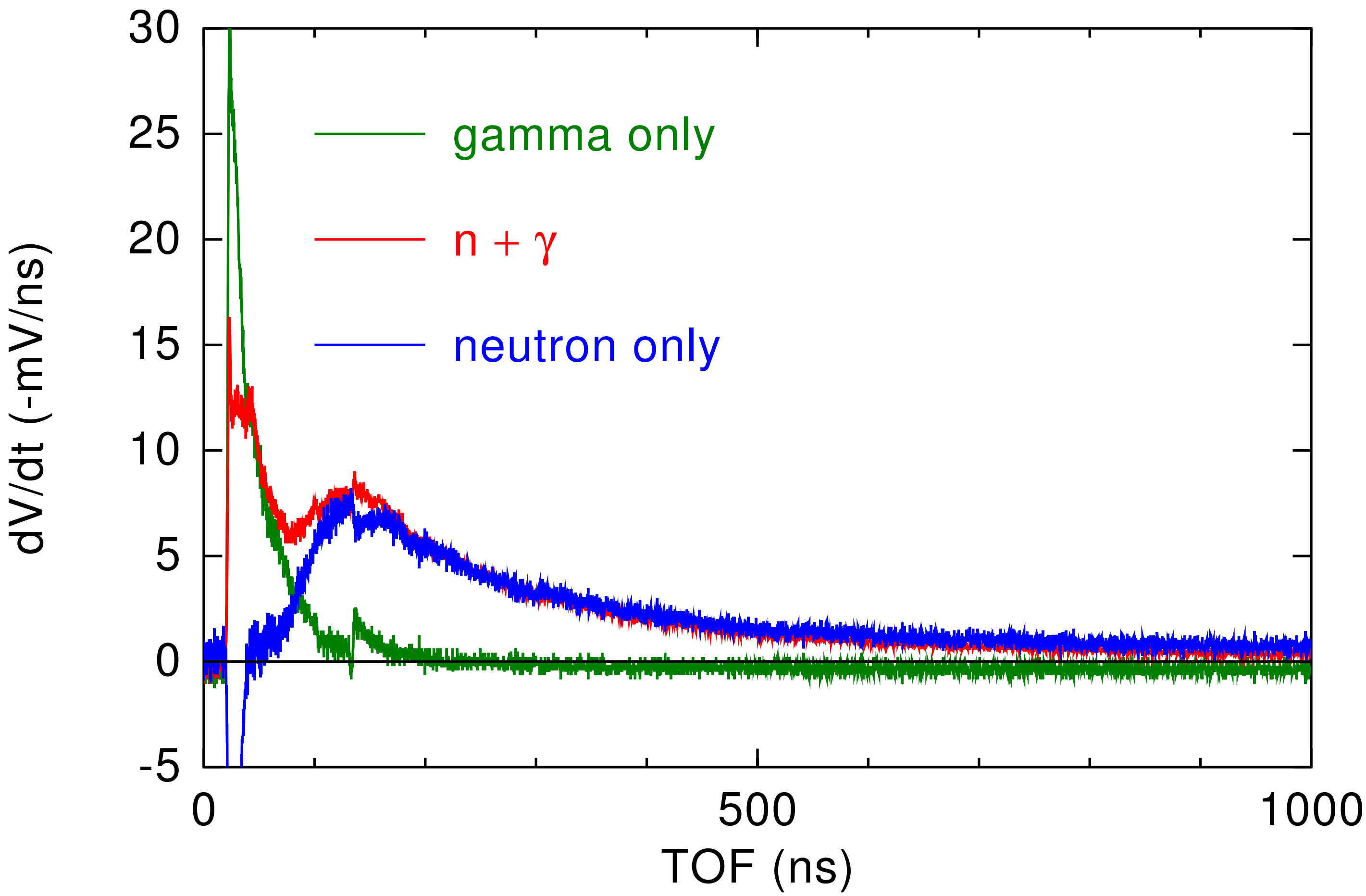


...and with higher neutron flux:

$\approx 1.5\text{–}2 \times 10^{10}$ n/sr/pulse

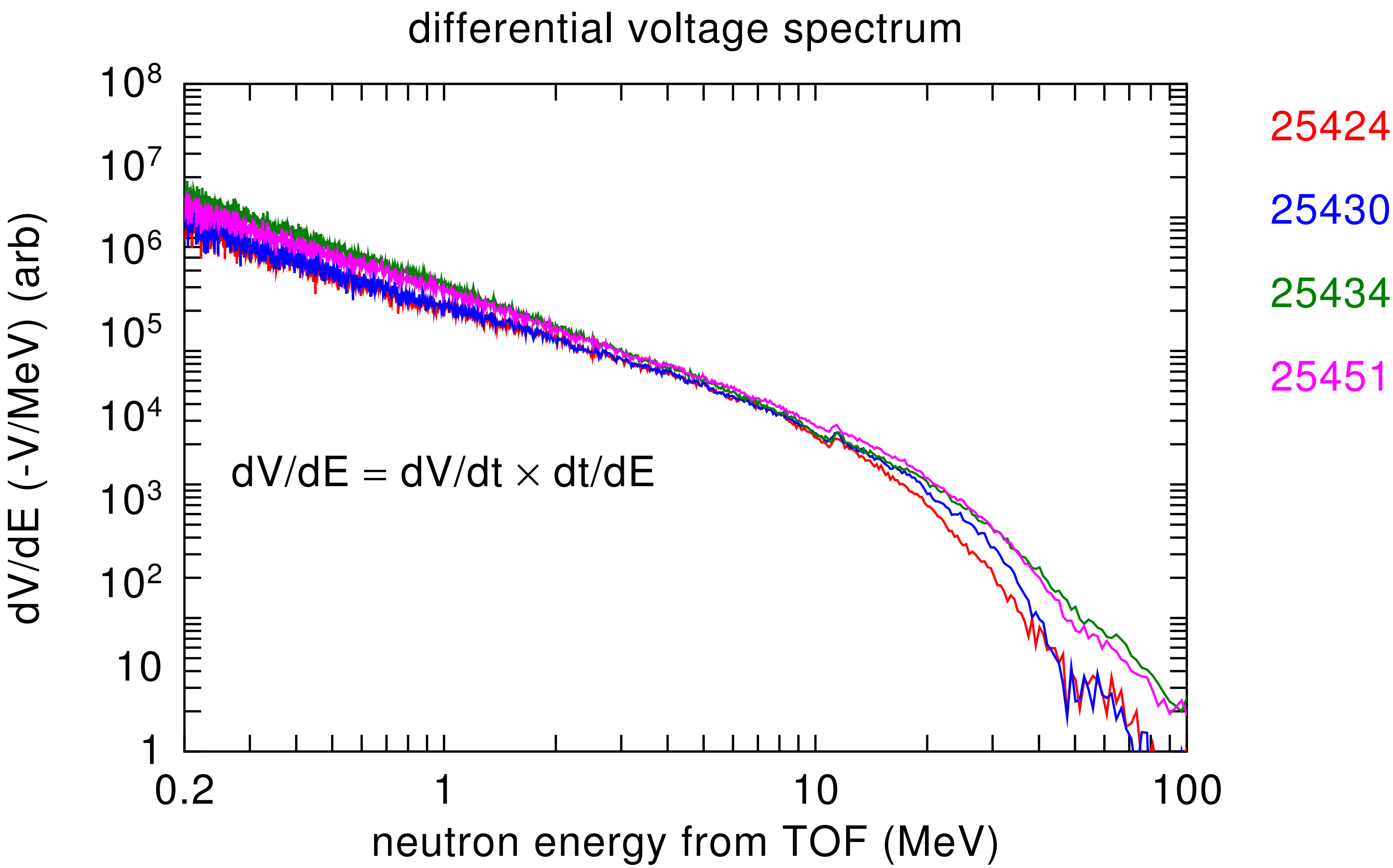
Four high-intensity neutron-production shots and one gamma-only shot were selected for analysis

subtraction of the gamma spectrum yields a neutron-only spectrum



newdata.plt: 11 Jul 2018 07:28:24

Proper conversion from TOF to energy reveals a true(r) spectral shape (light output)



dnde.plt: 11 Jul 2018 07:36:47

Current-mode neutron detection cannot be analyzed in the same way as pulse-mode detection

Pulse-mode detection:

- Number of counts in each TOF bin is proportional to the number of neutrons incident on the detector in that time interval
  - neutron detections are accumulated over multiple accelerator pulses
  - tens or hundreds of pulses to detect a single neutron in a given TOF bin

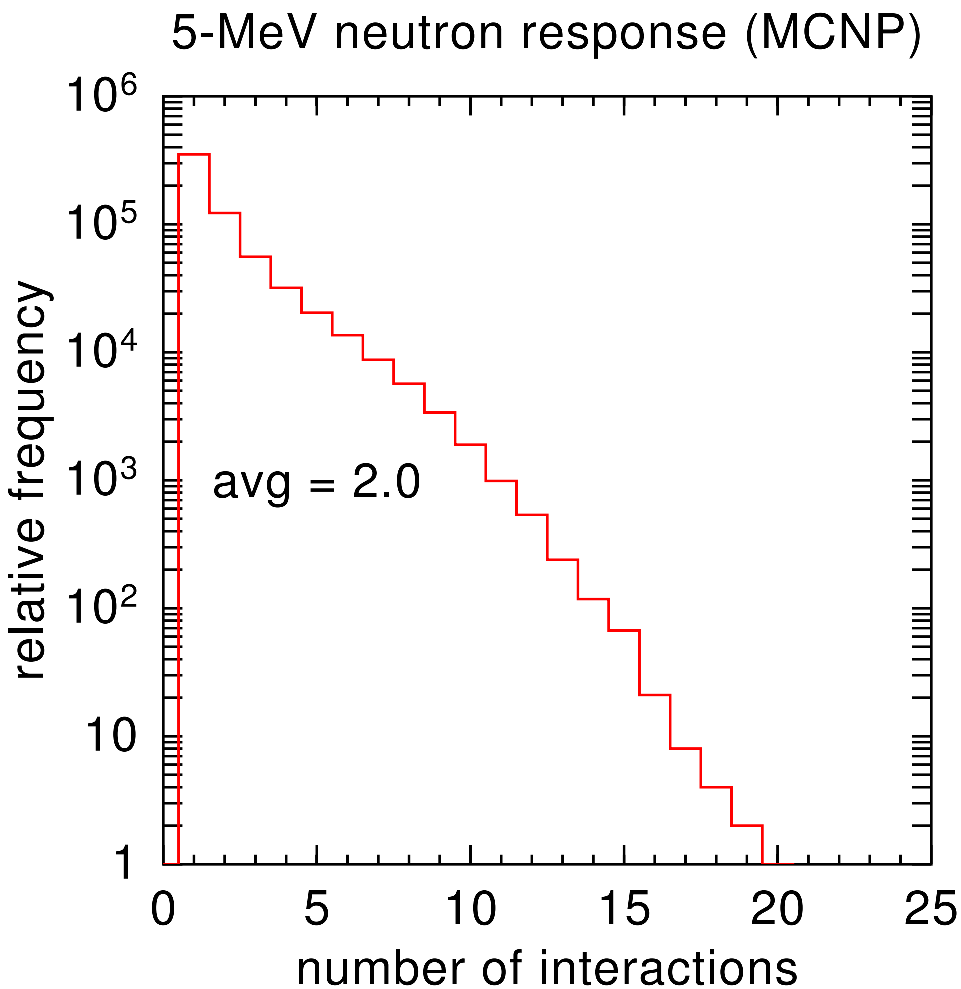
Current-mode detection:

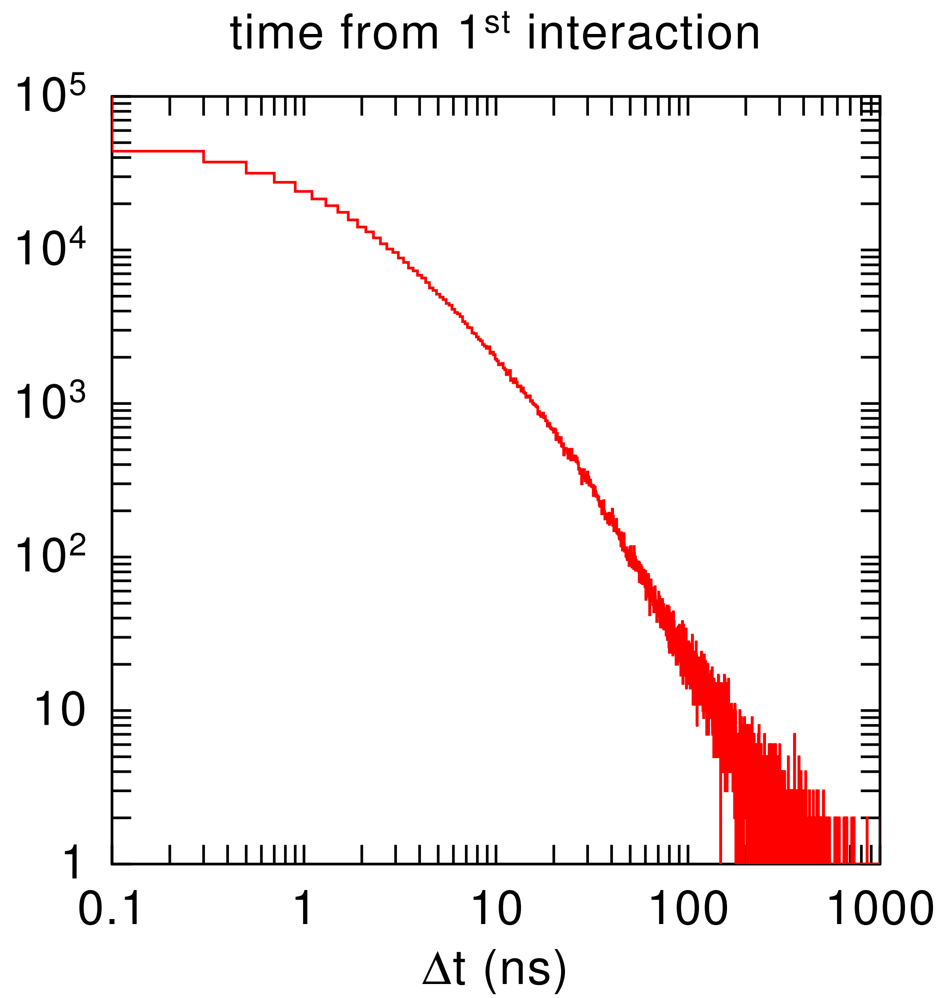
- The voltage recorded in each TOF bin is proportional to the amount of light emitted by neutron interactions in that time interval
  - a single laser pulse produces many neutrons (~$10^6/\mu s$) in the detector
  - tens or hundreds of neutron interactions/ns

Each neutron history may involve multiple interactions in the detector

- Pulse-counting:
  - TOF and PH values are derived from the sum of all interactions of a specific neutron
  - Low-energy recoils have minimal effect (only threshold crossing is important)
- Current mode:
  - specific neutron identities (histories) are unimportant
  - The PH vs TOF of all interactions are histogrammed separately
  - All recoils contribute to final spectrum.
  - Light emission must be calculated for very low-energy recoils.
  - Empirical light curves are inadequate for low energies (< 200 keV)

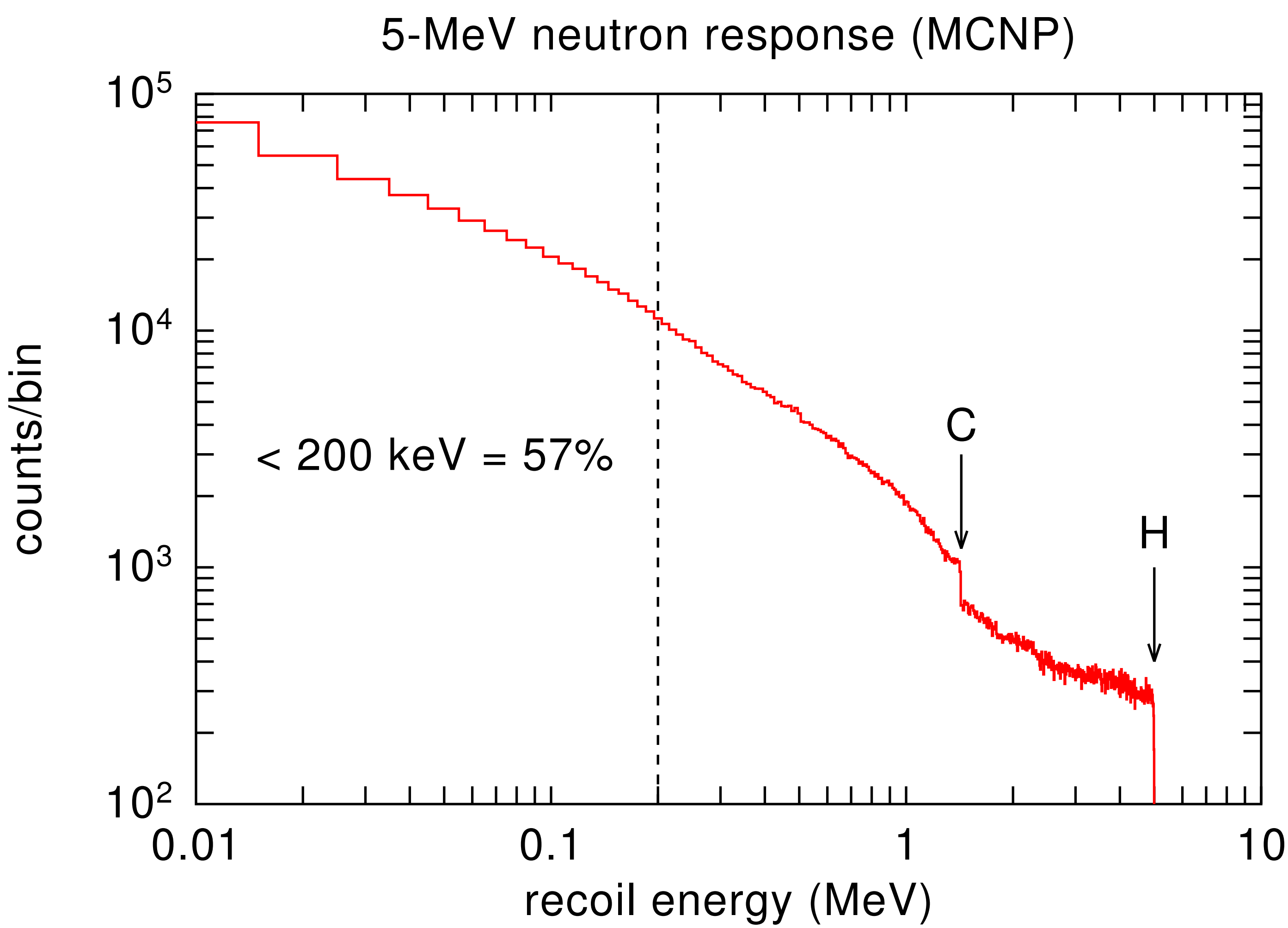
Neutrons can interact many times over a long time period





multi.plt: 11 Jan 2018 16:34:13

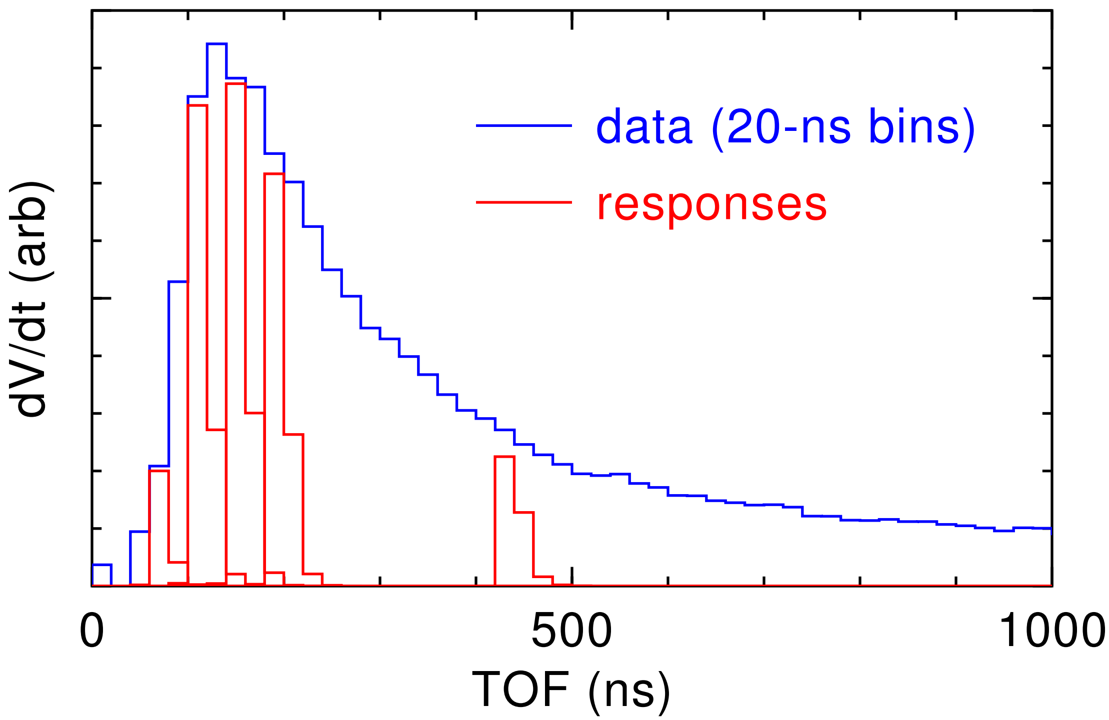
Low-energy recoils are extremely important



recoil.plt: 11 Jan 2018 15:30:30

Two assumptions are required for successful analysis of the current-mode data

- detector current is linearly proportional to the light output of the scintillator (detector mods mentioned previously)
- The TOF spectrum can be described as a linear combination of overlapping monochromatic response functions



analysis-3.plt: 10 Jul 2018 21:05:35

Analysis strategy utilizing MCNP (PoliMi)

- calculate light curves for p, α, C recoils
- measure, fit, and test the effect of PMT pulse shape
  - gamma and neutron source waveforms
  - gamma-flash waveform
- calculate MCNP response functions for 20-ns TOF bins
- extract energy spectrum (MCNP normalization factors) by matrix inversion
- validate the deconvolution method by testing on generic source terms:
  - maxwellian (T=2,6 MeV)
  - power law (aE^{-b})
  - flat spectrum
- validate derived experimental spectrum by using as source term in MCNP

Birk's formula for light output from an organic scintillator

Birk's formula (1951) (see Knoll or Leo):

$$\frac{dL}{dx} = \frac{S\,\frac{dE}{dx}}{1 + kB\,\frac{dE}{dx}} \longrightarrow L(E) = S\int_0^E \frac{1}{1 + kB\,\frac{dE}{dx}}\,dE$$

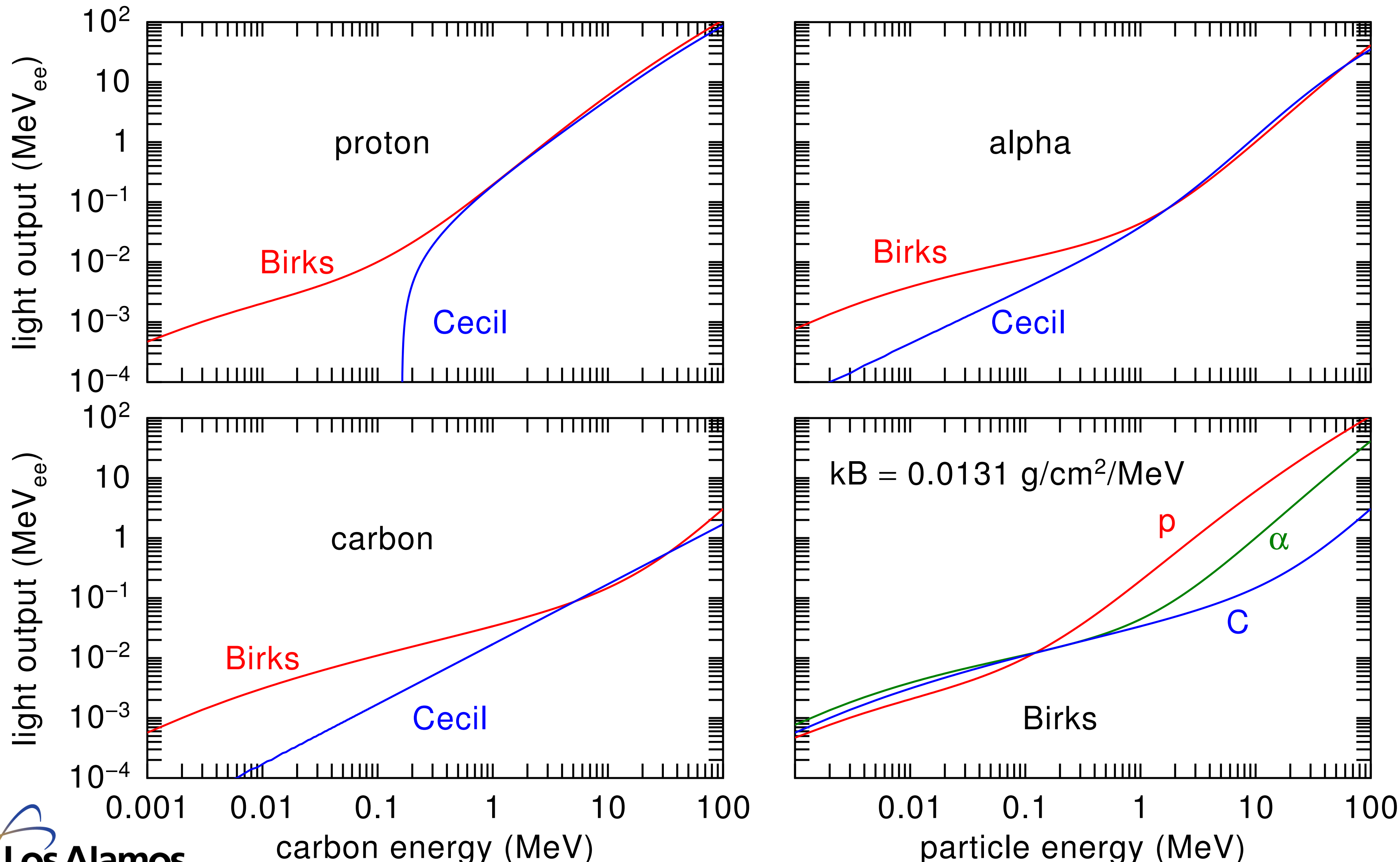
NE-102 experimental fit: $kB = 13.1 \times 10^{-3}$ g/cm^2/MeV (Craun)

dE/dx (MeV/g/cm^2) @ 1 MeV = 272 p

2456 α

5926 C

Calculated (Birks) vs empirical (Cecil) light output for NE102



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light_all.plt: 11 Jul 2018 06:29:56

The energy spectrum was unfolded by fitting the data with calculated response vectors

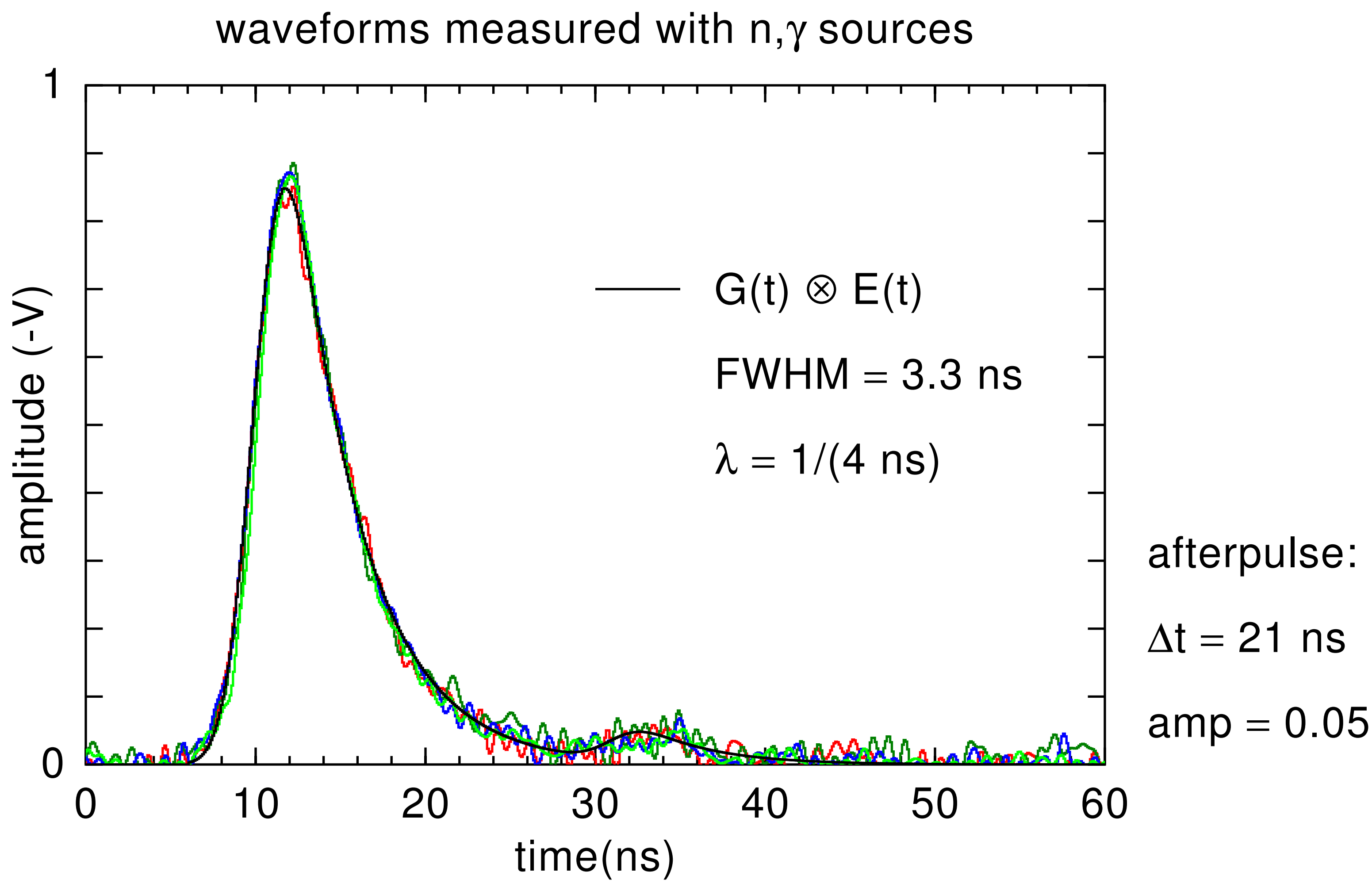
Two types of MCNP response vectors were considered

- Monoenergetic response (m):
  - single energy corresponding to center of each 20-ns TOF bin
- bin-wide response (w):
  - constant dN/dE spanning each 20-ns TOF bin

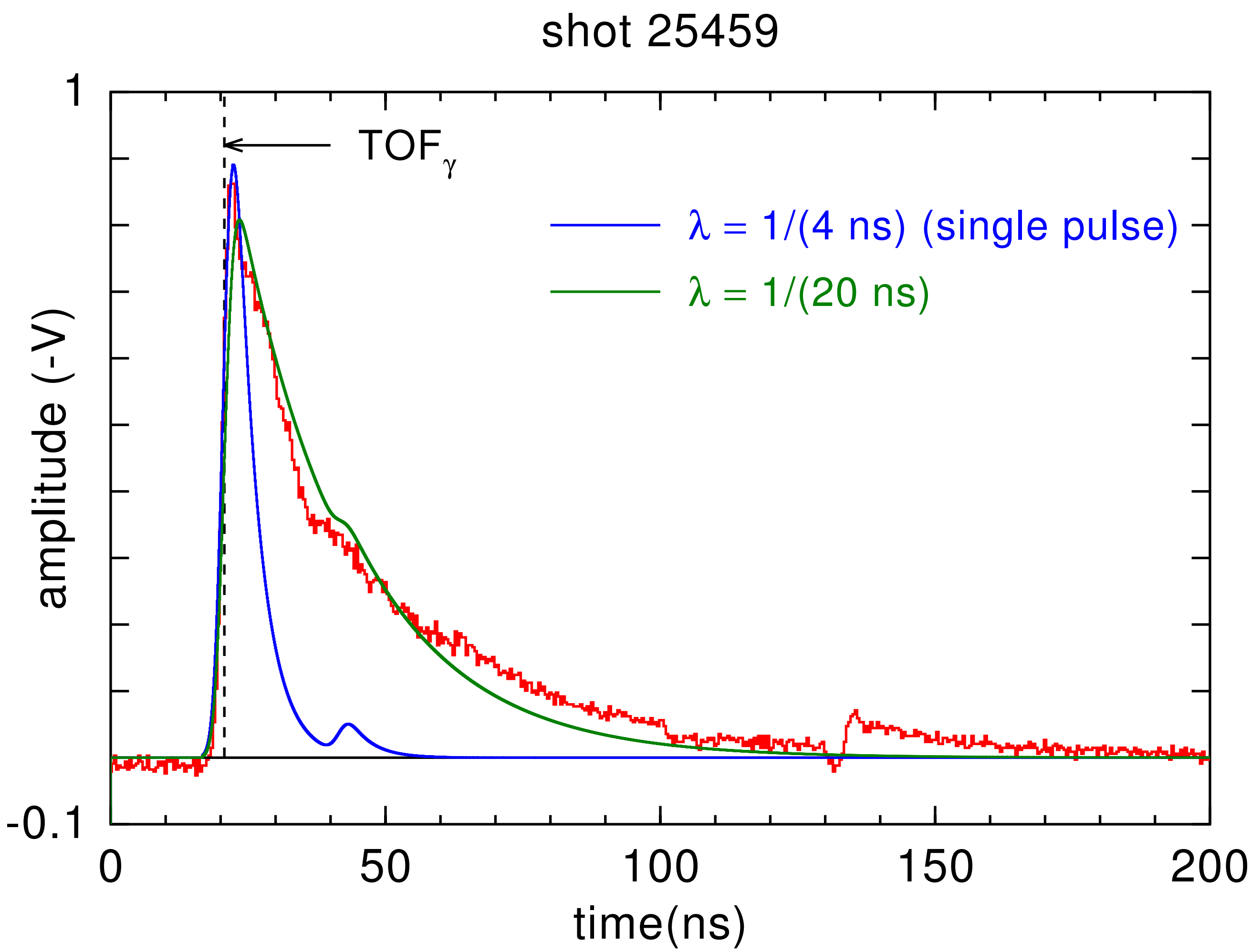
The MCNP light distribution was then smeared out in three ways:

- none : m0, w0 (no additional smearing)
- short: m2, w2 (from n,γ-source measurements: $\lambda = 4$ ns)
- long : m3, w3 (from Trident γ-flash: $\lambda = 20$ ns)

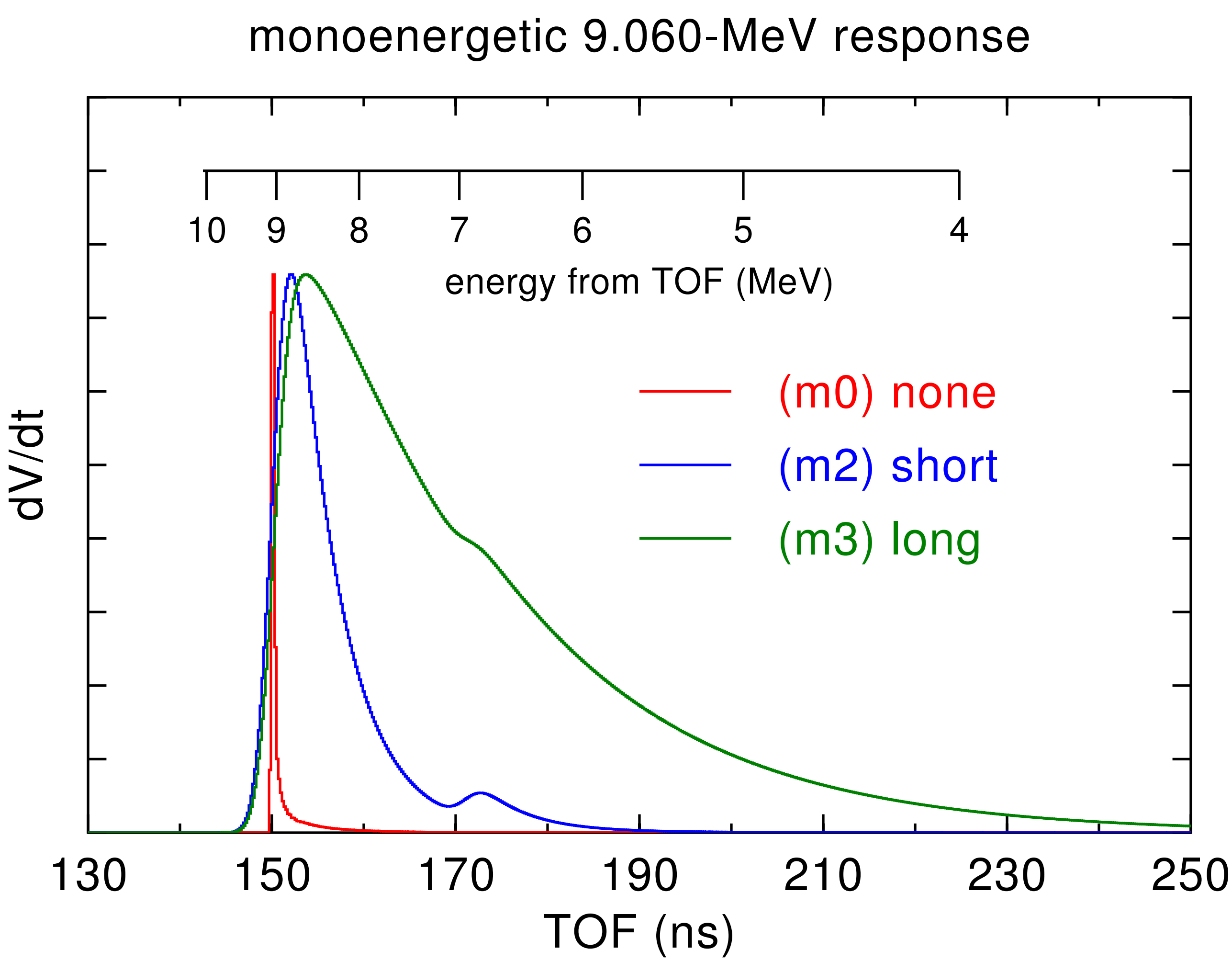
The detector pulse-shape is well described as a Gaussian folded with a step-exponential



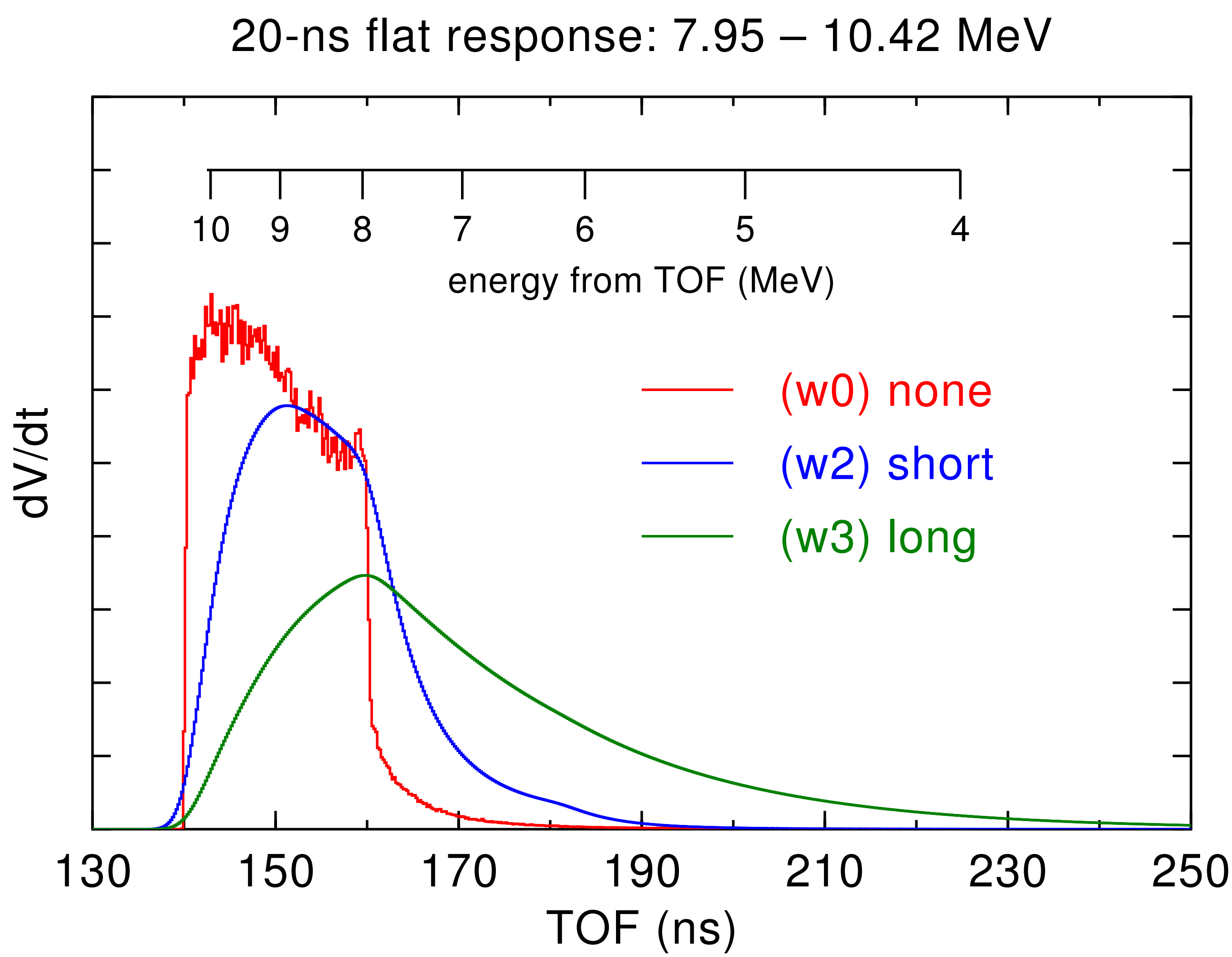
The shape of the gamma-flash oscilloscope trace cannot represent the actual time-distribution of gamma rays



Three light distributions were used to form the monoenergetic (m) MCNP response functions



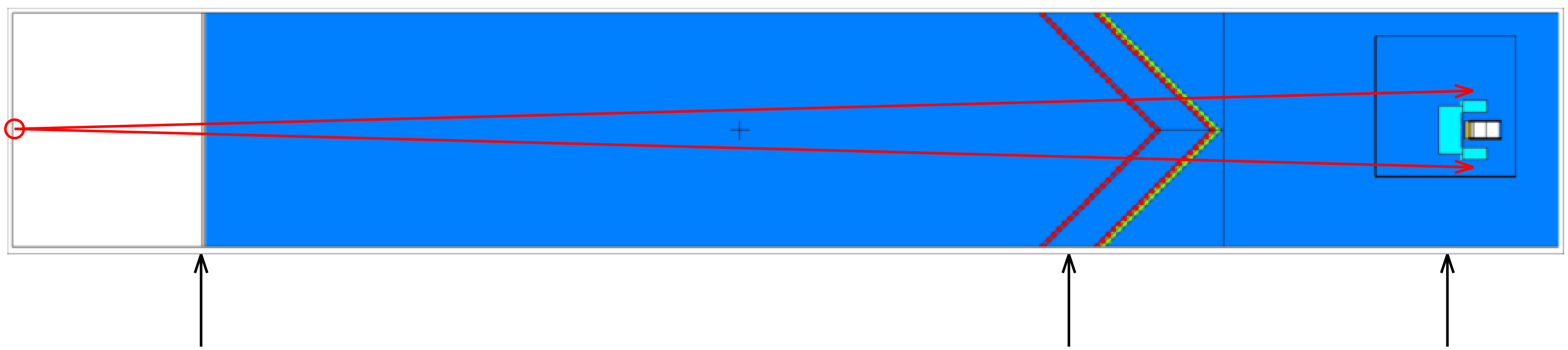
Three light distributions were used to form the bin-wide (w) MCNP response functions



response3.plt: 07 Mar 2018 14:04:45

A narrow beam was used for high-statistics MCNP calculations

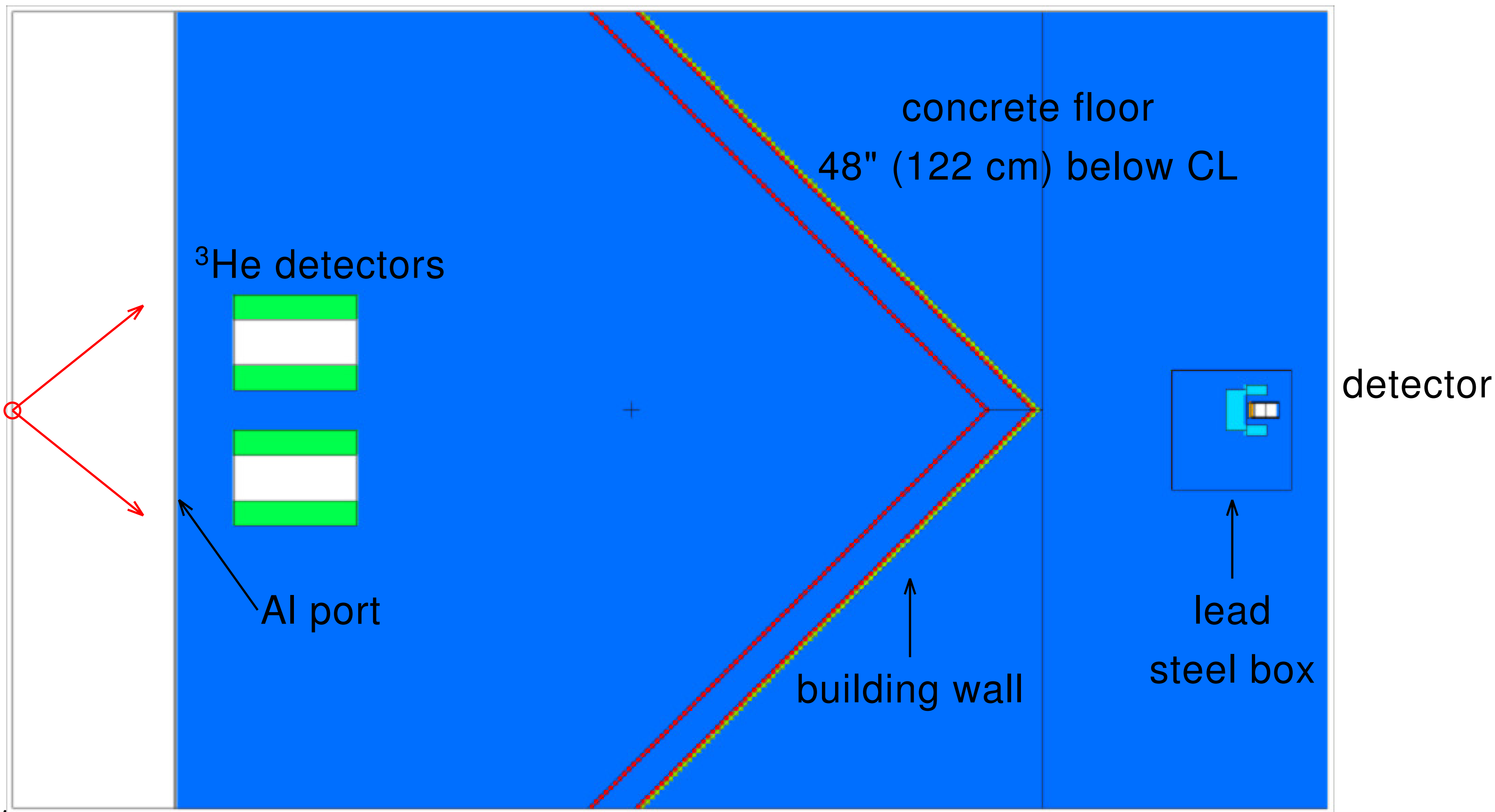
beam width (3.0°) = 32.5 cm at detector position (6.2 m)



geom1.plt: 07 Mar 2018 16:36:39

A wide beam was used for maximum-scatter MCNP calculations

beam width (67.4°) = 8.27 m at detector position (6.2 m)



geom2.plt: 07 Mar 2018 16:38:11

The MCNP response normalization factors are determined by matrix inversion

8 × 8 matrix example (m0 responses)

TOF	data	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	
50	70.97	5436276.8	0	0	0	0	0	0	0	N_1
70	156.40	48686.9	1581142.3	0	0	0	0	0	0	N_2
90	396.62	3848.9	29934.2	708131.0	0	0	0	0	0	N_3
110	637.98	855.7	2375.4	21112.4	477732.6	0	0	0	0	N_4
130	706.52	290.8	520.7	1632.8	15513.9	382391.9	0	0	0	N_5
150	661.85	126.2	175.8	348.6	1241.6	14172.0	303150.9	0	0	N_6
170	650.20	63.9	75.3	113.6	265.8	1182.1	9946.6	253724.4	0	N_7
190	563.58	36.6	39.7	49.3	88.5	262.9	920.7	8172.5	177420.9	N_8

- m0,m2,m3,w0 responses = lower triangular matrix
  - solve by forward-substitution (FS)
- w2,w3 responses:
  - solve by Gauss-Jordan (GJ) elimination

energy spectrum:

$(dN/dE)_i = N_i /(dE/dt)_i$

The deconvolution method was validated using several MCNP-generated spectra

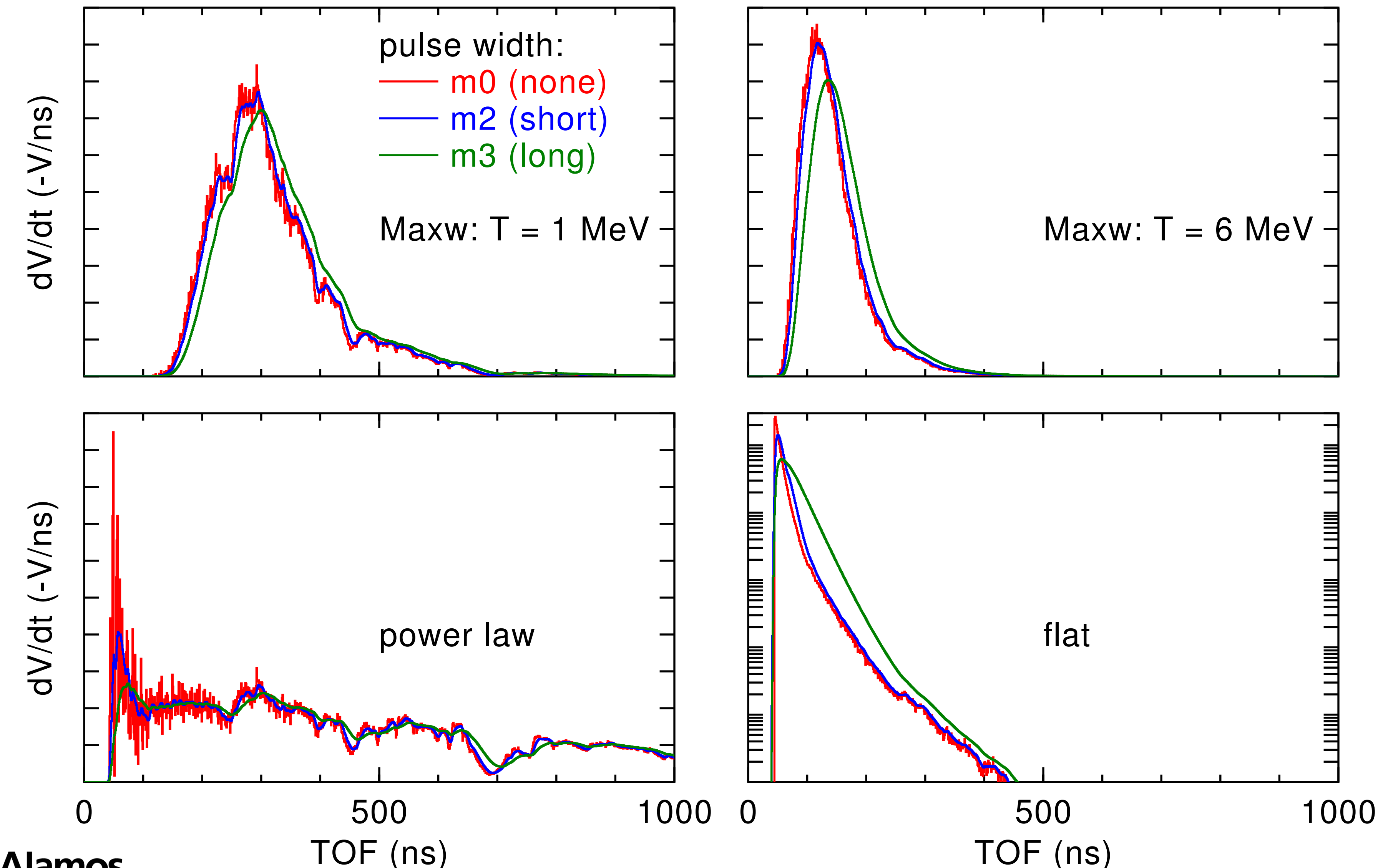
TOF spectra were generated with MCNP using four source distributions:

- Maxwellian, T=1 MeV
- Maxwellian, T=6 MeV
- power law: aE^{-b} (b = 2.42 based on early analysis)
- flat: dN/dE = constant, 0 – 120 MeV

The MCNP light distribution was then smeared out using the three previously described methods: none, short pulse, long pulse.

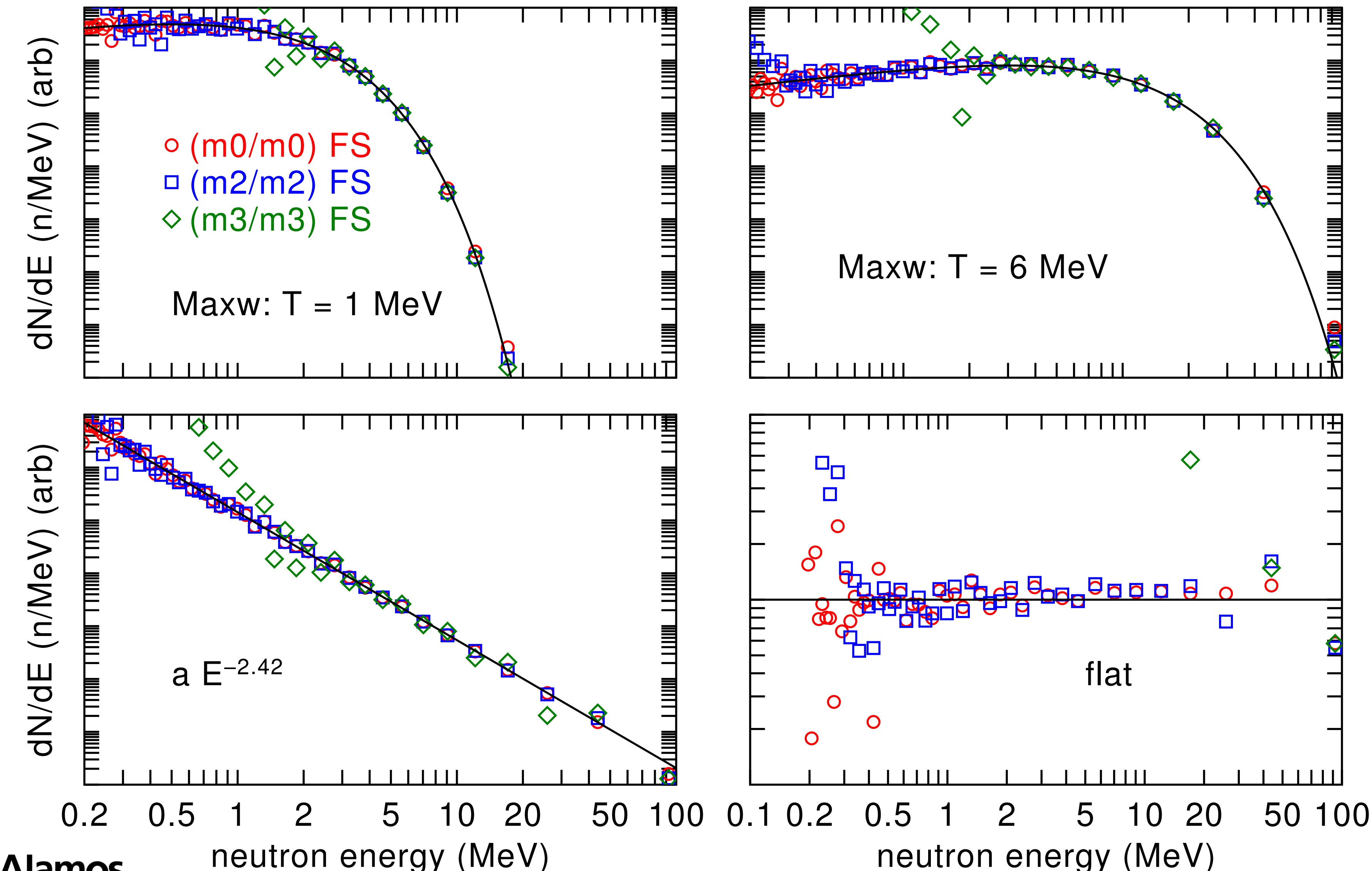
Each spectrum was then deconvolved with the corresponding response functions.

Four different source terms were used to generate TOF spectra with MCNP



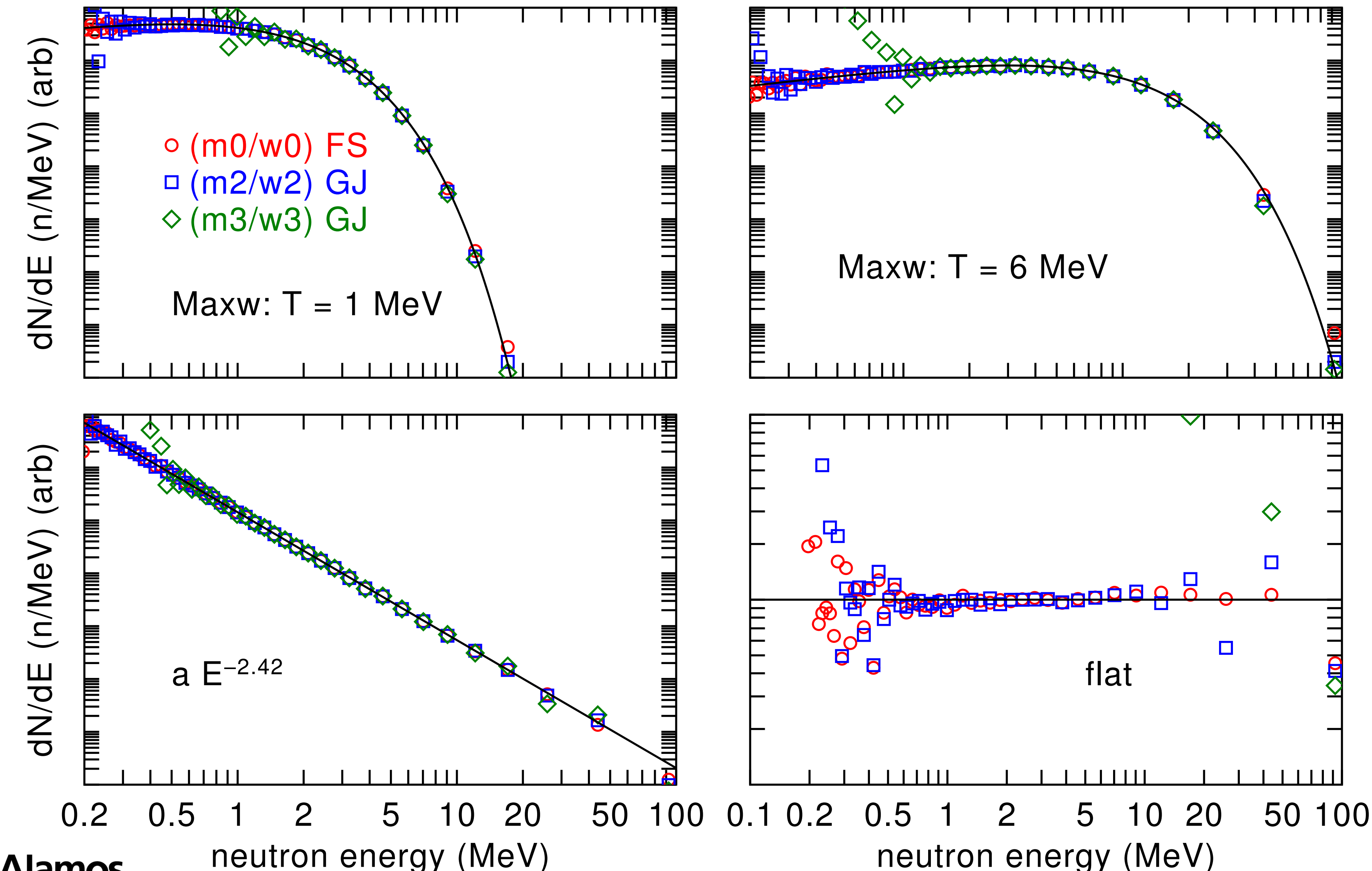
dndt_all.plt: 11 Jul 2018 06:55:13

Deconvolution of MCNP spectra with monoenergetic (m) responses



dnde_m.plt: 10 Jul 2018 23:00:33

Deconvolution of MCNP spectra with bin-width (w) responses



dnde_w.plt: 10 Jul 2018 23:17:37

Deconvolution accuracy is best judged by looking at ratios

Extracted spectra all look good on a log-log scale.

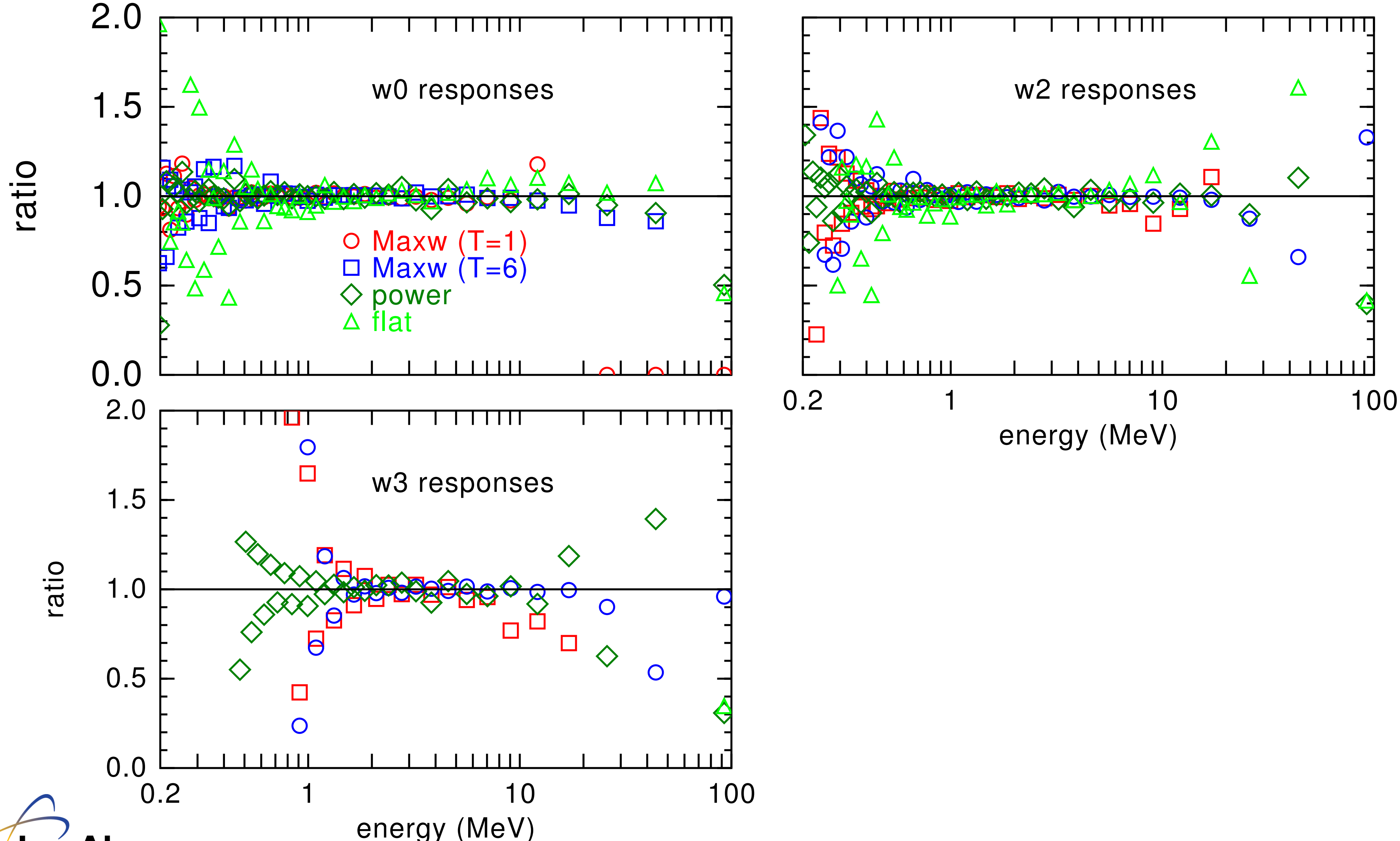
Ratios reveal that w0 and w2 fits work best.

- accuracy is better than about 10% except near endpoints of spectra
- w3 responses work well only between about 1 – 10 MeV
  - long-pulse shape is not well understood or easily verified

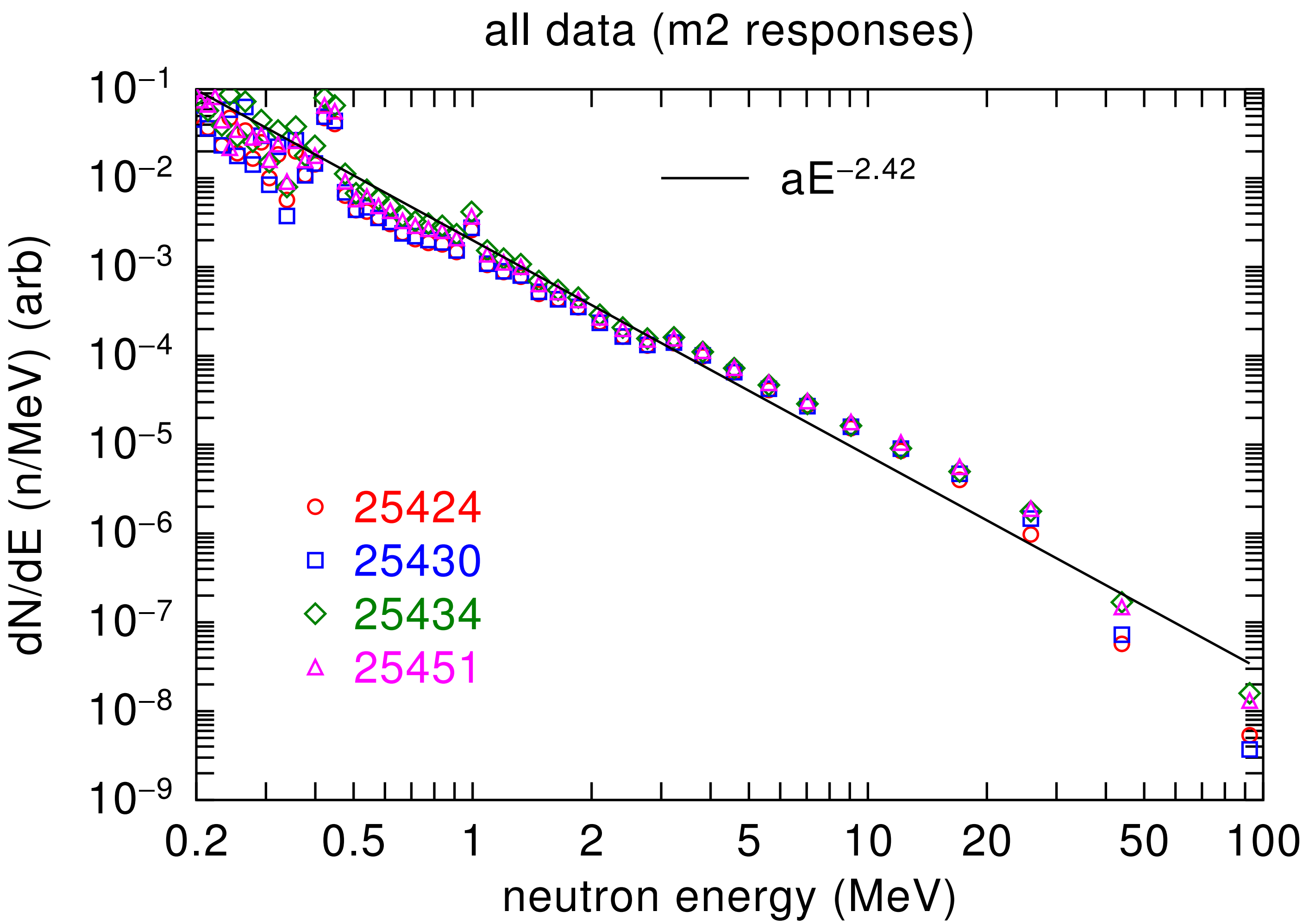
The w2 responses are best for analyzing real data:

- bin-wide response averages over relevant resonances, etc.
- short-pulse shape is verifiable and repeatable in lab measurements

Ratio of extracted spectrum / source spectrum



Neutron energy spectra extracted from all shots with monoenergetic responses



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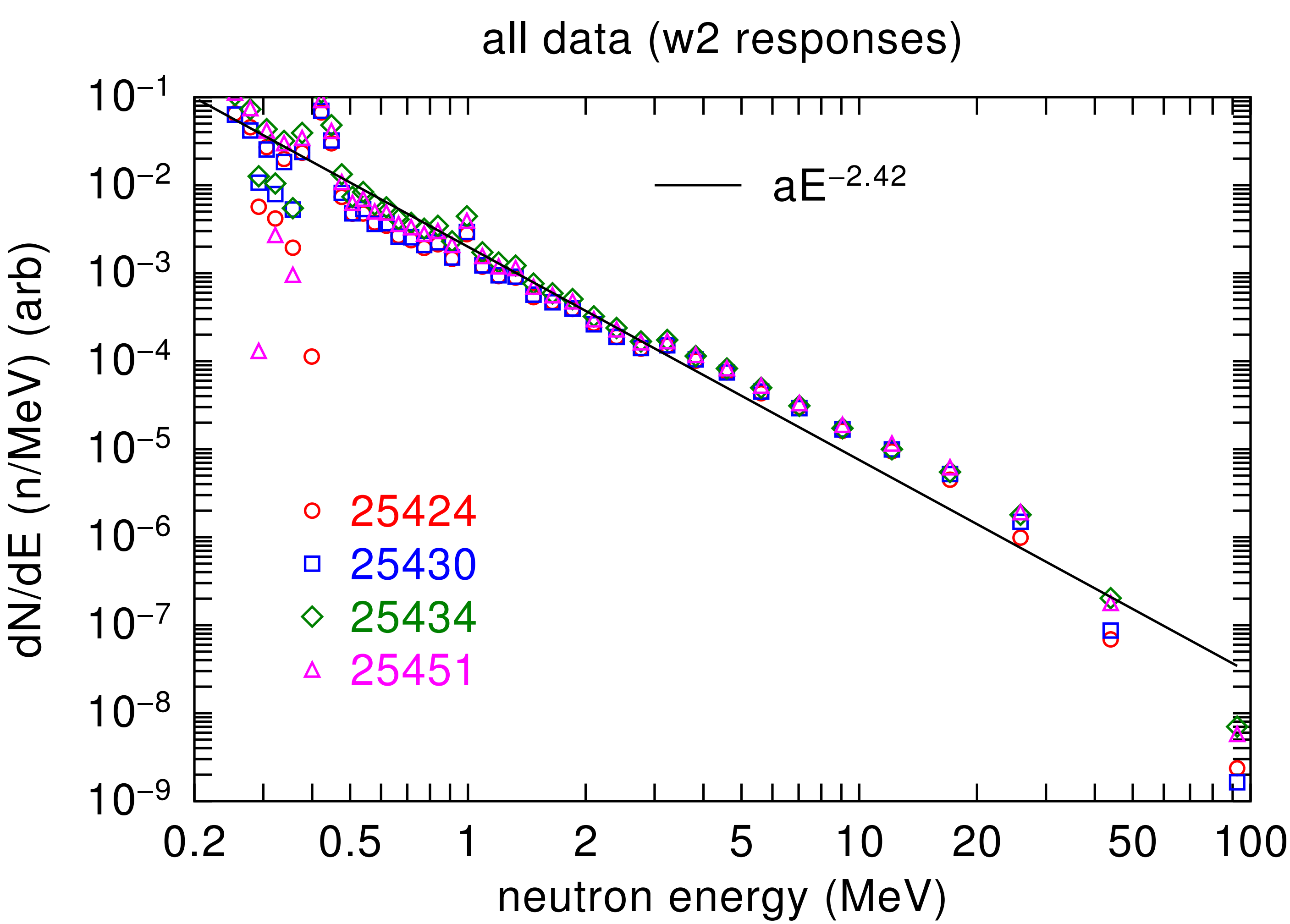
dnde-all_m2.plt: 11 Jul 2018 13:18:58

Neutron energy spectra extracted from all shots with bin-width responses



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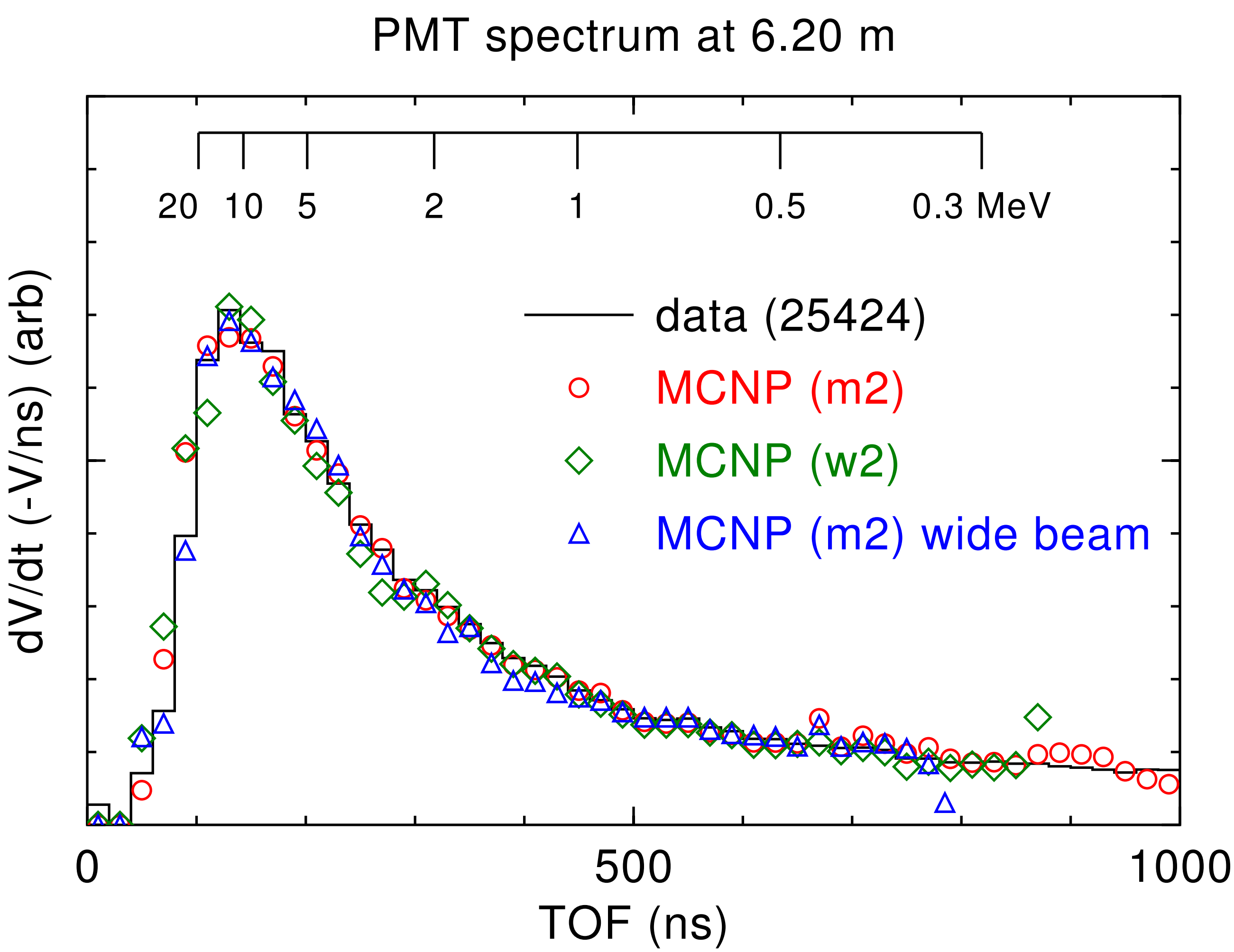
dnde-all_w2.plt: 11 Jul 2018 13:19:34

The data are well reproduced with the derived neutron spectra



tof4.plt: 08 Mar 2018 06:52:22

Analysis Summary

MCNP response functions were calculated with several variations:

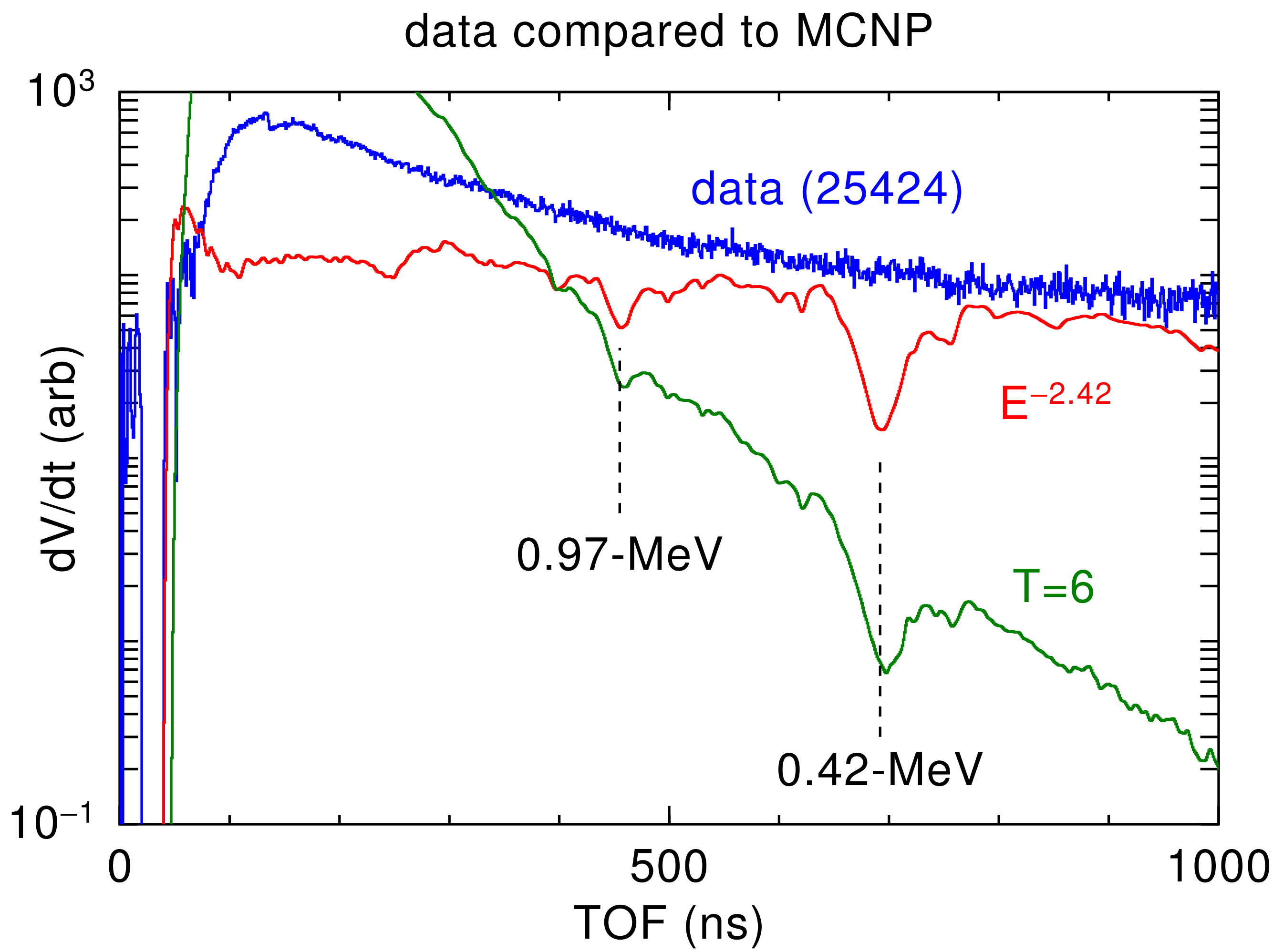
- PMT pulse shape: none, short decay, long decay
- monoenergetic (bin center), bin-width (constant dN/dE)
- narrow beam (high statistics),wide beam (maximum scattering)

All variations yield consistent results down to about 0.5 MeV

- the short-decay, bin-width responses (w2) give the preferred solution
- derived spectrum resembles a power law (aE^{-b}) (roughly!)

but, there are still some issues....

Maxwellian and power-law MCNP spectra show absorption dips that are not present in the data



Some unanswered questions remain

Some spectral features (absorption dips) predicted by MCNP are not seen in the data

- incorrect or incomplete MCNP model?
- PMT performance not understood?
  - pulse shape in (γ,n) bench measurements different from current-mode laser environment

Acknowledgements

The experimental results presented here were obtained as part of an LDRD project to develop a short-pulse laser-driven neutron source for active interrogation of nuclear material.

The nTOF detector system was designed and built by:

- K. Ianakiev
- M. Iliev

Bibliography

- "Improved predictions of neutron detection efficiency for hydrocarbon scintillators from 1 MeV to about 300 MeV",
  R.A. Cecil, B.D. Anderson, R. Madey, Nucl. Instrum. Methods 161, 439 (1979).
- "Analysis of response data for several organic scintillators",
  R.L. Craun and D.L. Smith, Nucl. Instrum. Methods 80, 239 (1970).
- "Radiation Detection and Measurement", Glenn F. Knoll, John Wiley & Sons, New York, 1979.